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Analysis and Implementation of Full-Wave Single-Phase Controlled Rectifier for AC Motor Speed Control

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Abstract

Speed control of AC motors is an important aspect in optimizing the performance of electromechanical systems in a variety of engineering applications. Some commonly used methods include frequency regulation, changes in the number of pole pairs, the use of external resistance, anchor voltage regulation, and vector controllers. This approach can be integrated with modern power electronics, such as thyristors and TRIACs, to improve the efficiency of control systems. Induction motors are often operated under partial load conditions, which can hamper system performance due to decreased power efficiency and power factor. This study proposes the implementation of a TRIAC-based controlled rectifier to regulate the speed of AC motors through input voltage modification. The system utilizes a TRIAC firing angle that is set using a variable resistor or potentiometer to adjust the voltage received by the motor, so that the rotor speed can be controlled as needed. By implementing this approach, power efficiency can be improved, and the disadvantages of using induction motors at partial loads can be mitigated. This study presents simulations, experimental designs, and system performance analysis to prove the effectiveness of this method in improving the efficiency and flexibility of AC motor control.

Keywords: Single Phase AC Motor, Speed Control, Bidirectional Triode Thyristor (TRIAC), Power Electronics.

1. Introduction

In the modern era, the development of electronic technology has brought various advances in human life, especially with the presence of various electronic devices that utilize semiconductor components. One such component is TRIAC, which is a high-speed semiconductor device that functions as a power link in AC control applications (Gurevich, 2008). TRIAC is capable of operating at voltages above 100V and currents over 100A, so this component is often used in AC power control systems such as light intensity regulation (lamp dimmer), heating control, and motor speed regulation (Trisna Nugraha et al., 2019).

In the context of AC motor control, TRIAC is a very important solution. AC motors are widely used in a variety of industrial and household applications due to their advantages, such as their simple design and low maintenance costs (Fitzgerald et al., 2003). The rotational speed of an AC motor can be controlled by several methods, including voltage and frequency regulation. Synchronous motors, a type of AC motor, have a constant speed that is directly proportional to the frequency. Synchronous motors also have advantages such as the ability to operate on lagging and leading power factors and high efficiency because there is no slip that can cause power loss (Rashid, 2017). However, the main disadvantage of synchronous motors is that they do not have a starting torque, so they require a special method to start the operation (Mohan et al., 2003).

In this study, TRIAC is used as a speed controller for single-phase AC motors. By utilizing the TRIAC working principle that regulates the input voltage of the motor through the firing angle, the system can provide precise and flexible speed control according to the load requirements. This approach provides efficient and easy-to-implement solutions in a variety of engineering applications, both for industrial and household needs (Hamid et al., 2020).

2. Material and methods

2.1. Material

2.1.1 Rectifier Circuit

Rectifier circuits play a fundamental role in converting alternating current (AC) into direct current (DC). The core component of these circuits is the diode, which allows electric current to flow in one direction while blocking it in the opposite direction. As a result, when powered by an AC current, the diode permits only half of the wave to pass, while the other half is blocked. Based on Moorthy (2005), Lander (1993), and Singh and Kanchanadhani (2007), rectifier circuits are broadly categorized into uncontrolled rectifiers, half-controlled rectifiers, and fully-controlled rectifiers. Depending on the wave output, rectifier circuits are further divided into

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half-wave rectifiers and full-wave rectifiers. These classifications emphasize the versatility and applicability of rectifiers in various industrial and household devices.

2.1.2 Controlled Rectifier

A controlled rectifier is an advanced power electronics circuit designed to convert AC voltage to DC voltage with adjustable output. Semiconductor devices, such as silicon-controlled rectifiers (SCR), are pivotal in such systems, acting as switches and voltage regulators. The desired output voltage is achieved by controlling the gate terminal of the SCR. Controlled rectifier circuits are categorized into single-phase and three-phase systems based on the input voltage source. These configurations allow for precise control of the output voltage, making them suitable for applications such as motor drives, heating systems, and industrial automation (Hasad et al., 2011).

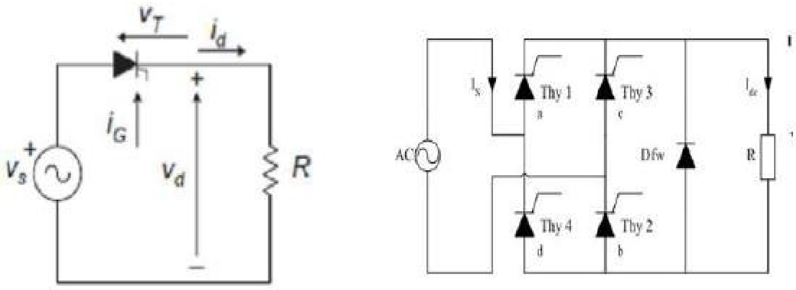

Figure 1. Single-phase half-wave (left) and full-wave (right) single-phase controlled rectifier circuit

2.1.3 Full-Wave Single-Phase Controlled Rectifier Circuit

The full-wave single-phase controlled rectifier circuit is a key technology for converting AC power into DC electricity. This circuit typically incorporates four SCRs, enabling control of the output voltage by adjusting the ignition angle. Within the circuit, two pairs of trigger pulses are required—one for the positive half-wave and another for the negative half-wave. Full-wave single-phase controlled rectifiers can be further classified into center-tapped (CT) configurations, bridge connections, and semi-controlled variants, providing flexibility for different power control applications (Prasetya, 2015).

The output voltage (DC) can be expressed as:

$$V_{o(dc)} = \frac{V_m}{\pi}[1 + \cos\alpha] \tag{1}$$

For the root mean square (RMS) output voltage:

$$V_{o(rms)} = \frac{V_m}{\sqrt{2}}\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}} \tag{2}$$

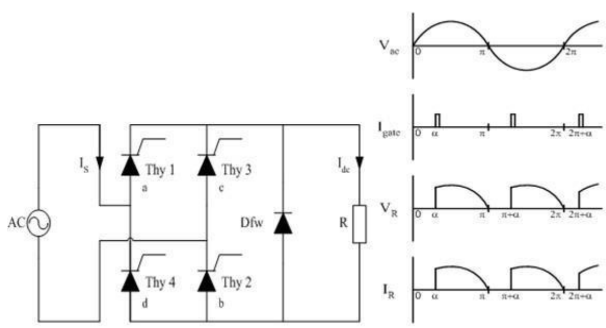

Figure 2. Full-wave single-phase controlled rectifier

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2.1.4 TRIAC

The Bidirectional Triode Thyristor, commonly known as TRIAC, is a vital component in AC power control systems. It can conduct current in both directions, triggered by either positive or negative voltages at its gate terminal. This bidirectional functionality simplifies the design and enhances the efficiency of AC power control applications, including motor speed control and light dimming. Unlike conventional SCRs, TRIACs can pass current in both directions when triggered, offering greater versatility in power control systems. According to Hasad et al. (2011), TRIAC designs are instrumental in enabling high-voltage switching and efficient power management in AC circuits.

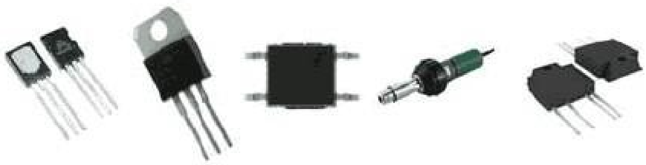

Figure 3. Physical form of TRIACThe TRIAC Work Initiative

2.1.5 Working Principle of TRIAC

TRIAC consists of four semiconductor layers (NPNP or PNPN), which determine its functionality based on the polarity of the applied current. The TRIAC operates in four triggering modes:

- **Mode I:** Negative gate current (-ve) and positive main terminal 2 current (+ve).
- **Mode I+:** Positive gate current (+ve) and positive main terminal 2 current (+ve).
- **Mode III:** Negative gate current (-ve) and negative main terminal 2 current (-ve).
- **Mode III+:** Positive gate current (+ve) and negative main terminal 2 current (-ve).

2.1.6 AC Motor

AC motors, categorized as electric motors powered by alternating current, comprise a stator and rotor. Single-phase AC motors, commonly used in household appliances such as fans and washing machines, operate on a single-phase power supply. These motors are preferred for their compact size and ability to function in smaller commercial applications. The speed of an AC motor can be controlled by adjusting the input voltage using power electronic components like TRIACs. This approach enables effective speed regulation and minimizes power consumption, making AC motors an efficient solution for various applications despite their limitations compared to three-phase motors (Prasetya, 2015).

2.2 Methods

In the preparation of this paper, the author employs a literature study method, a widely recognized approach in technical and engineering research. This method involves the utilization of various written sources, such as books, journal articles, and internet-based references, which provide foundational insights into the topics being discussed. The purpose of this method is to review existing knowledge, identify gaps, and build upon previously established research, thus contributing to the body of knowledge in the field of electrical and electronic engineering.

2.2.1 Software Utilization

For simulating the full-wave single-phase controlled rectifier circuit, the software selected for this study is PSIM. PSIM is a powerful simulation tool extensively used in the field of power electronics and electrical engineering for analyzing and designing systems like power converters, control systems, and electrical machines. Developed by Power Sim Inc., PSIM allows for the modeling of complex circuits and systems, providing essential insights into the behavior of electrical components under various conditions. This software will be employed to simulate the performance of the full-wave single-phase controlled rectifier and its impact on the motor control system, as outlined in the objective of this study.

2.2.2 System Requirements Analysis

A thorough system requirements analysis is crucial in the early stages of the simulation process. It ensures that the necessary components and parameters are identified, which are vital for a successful simulation. The analysis involves determining the tools, materials, and equipment that are required to accurately model the full-wave single-phase controlled rectifier circuit within the PSIM environment. The components selected for this study include:

a. **Variac (Variable Alternating Current):** To adjust the AC voltage input and simulate different operational conditions for the rectifier.

b. **Single-phase Transformer:** To step up or step down the input AC voltage as required for the rectifier operation.

c. **TRIAC:** As the key semiconductor device for controlling the rectification process and regulating the output DC voltage.

d. **Resistor:** Used to limit current flow and control power dissipation in the circuit.

e. **Ammeter:** To measure the current passing through the circuit, ensuring that the system operates within specified limits.

f. **Voltmeter:** To measure the voltage across components, ensuring that the system's voltage characteristics meet expectations.

g. **Oscilloscope:** To observe the waveform of the rectified output and verify the quality of the conversion.

h. **AC Motor:** The load for the rectifier system, which will be controlled by the regulated DC voltage output from the rectifier.

2.2.3 System Block Diagram

A system block diagram is a simplified representation of the various components and their interconnections in the simulation model. It provides a clear visual understanding of the relationships between the different devices and processes involved in the controlled rectifier system. The block diagram serves as the conceptual framework for the simulation, outlining the flow of electrical energy from the AC input to the DC output, as well as the control mechanism for regulating the output.

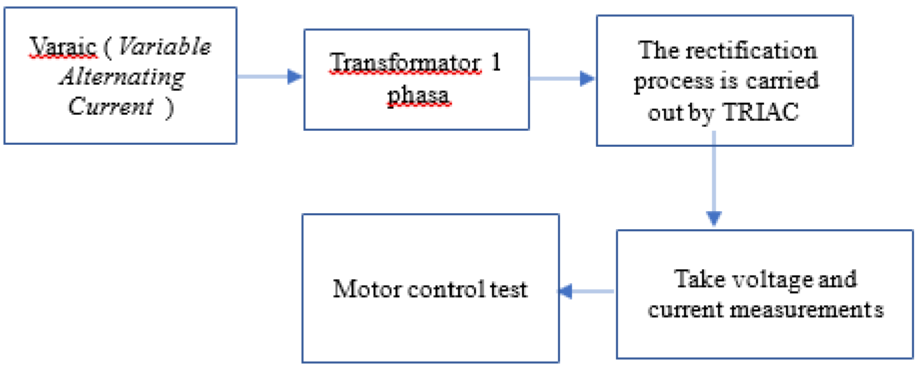

Figure 4. Block Diagram System

2.2.4 System Flowchart

The flowchart serves as a step-by-step diagrammatic representation of the control process in the system. It outlines the logical sequence of operations from the initiation of the simulation, through the rectification process, and to the control of the motor speed. The flowchart will guide the simulation process by providing a clear path for system behavior, helping to ensure the accuracy of the simulation.

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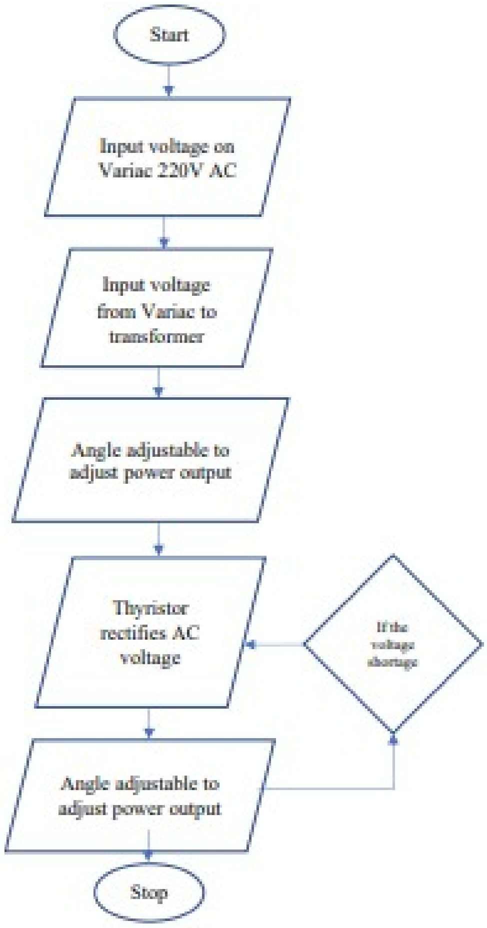

Figure 5. Flowchart System

2.2.5 PSIM Simulation Circuit

The simulation circuit within PSIM will be configured to accurately represent the full-wave single-phase controlled rectifier and its associated components. This section details how the PSIM environment is set up, including the input specifications, control parameters, and the rectifier configuration. The circuit will include all necessary components such as the transformer, TRIAC, and motor load, with corresponding settings to achieve the desired motor speed control via rectified DC output.

This section of the methodology outlines the approach to be taken in the simulation of the full-wave single-phase controlled rectifier. The systematic use of PSIM, along with careful selection of components and accurate system setup, will ensure that the model provides realistic insights into the performance of the rectifier for motor speed control. By employing such a simulation, the study will be able to validate the effectiveness of the controlled rectifier in the context of AC motor speed regulation, as discussed in the journal, seminar, and KTI requirements for engineering research.

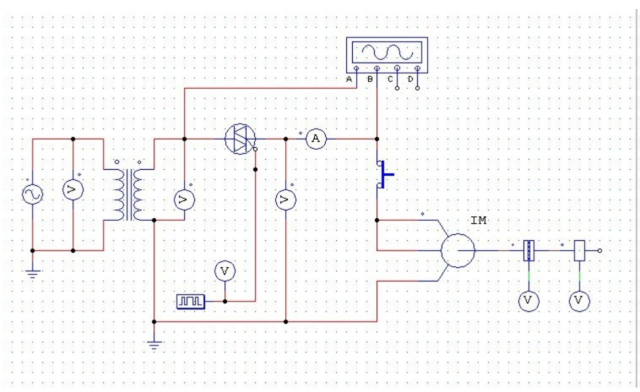

Figure 6. PSIM Simulation Circuit

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3. Results and discussion

3.1. Simulation on PSIM

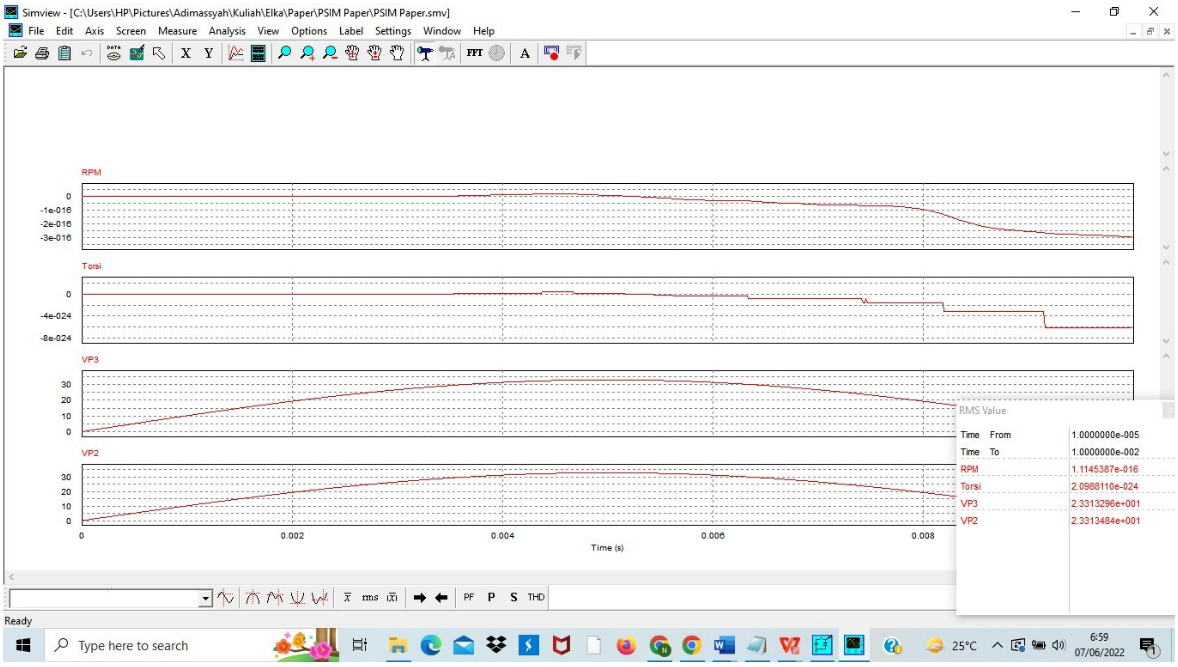

Figure 7. PSIM response graphic

The simulation conducted on the PSIM software produced a series of data representing the relationship between the trigger angle (α) of the TRIAC and the resulting voltage and current in the circuit. The following table summarizes the simulation results:

Table 1. summarizes the simulation results

No	Angle α	Source Voltage (V)	Load Voltage (V)	Load Current (A)
1	15°	230.4	224.3	0.26
2	30°	230.4	209	0.26
3	45°	230.4	186.9	0.26
4	60°	230.4	159.8	0.23
5	90°	230.4	100.1	0.2
6	120°	230.4	43.24	0.14

The results demonstrate the effect of increasing the TRIAC trigger angle (α) on the load voltage and current. As the angle increases, the voltage and current supplied to the load decrease significantly. This aligns with the theoretical expectations that a higher TRIAC trigger angle corresponds to a shorter conduction period, reducing the energy transferred to the load.

3.2. Motor Speed Control and Energy Efficiency

Based on the test results of the controller circuit, the single-phase controlled rectifier effectively regulates the speed of the AC motor. The rotary switch positions (ranging from one to six) correspond to different motor speed scales, with an inverse relationship observed between the rotary switch position and motor speed. Specifically, as the rotary switch position increases, the motor speed decreases. This reduction in speed corresponds to a decrease in the input current and, consequently, the power consumed by the motor. The lower power consumption demonstrates the energy-saving capabilities of the system.

The findings confirm that the system can dynamically control the motor speed while minimizing power consumption, making it a practical solution for applications requiring variable-speed AC motor operation.

4. Conclusion

Based on the analysis and experimental results, the single-phase full-wave controlled rectifier has proven effective in regulating the speed of AC motors while promoting energy efficiency. By adjusting the TRIAC trigger angle, the system successfully controls the load voltage, resulting in smooth and precise motor speed regulation. Furthermore, the reduction in input current as the TRIAC trigger angle increases highlights the energy-saving potential of the system, making it a viable solution for applications requiring variable-speed motor operation. The use of semiconductor devices, such as the TRIAC, offers significant advantages, including minimal additional components, smooth control, and low power losses, ensuring the system's reliability and cost-effectiveness. These findings demonstrate the practicality of the system in industrial and domestic settings, contributing to energy conservation efforts without compromising performance. Future studies could explore the integration of advanced control methods or additional components to further enhance system functionality and broaden its application scope, paving the way for more sustainable and efficient power electronics technologies.

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